National Aeronautics and Space Administration

CONCEPTUAL DESIGN OF QUANTUM-COHERENT PHASE-CONTROLLED LOW-LIGHT GaAs SWITCH FOR CONSTRUCTION OF FREE-SPACE OPTICAL COMMUNICATION QUANTUM RECEIVER

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Project Objective:

The main objective of this project is the theoretical investigation and conceptual design of a phase-controlled low-light level GaAs switch. Ultimately, the switch is intended for use in BPSK ("binary phase-shift key") quantum receivers for NASA's deep-space quantum communication.

FY09 Results:

We have laid the theoretical foundation for the use of GaAs quantum dots in phase-sensitive BPSK quantum receivers:

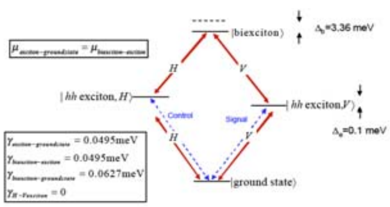
- we have used realistic relaxation parameters of disorder-induced quantum dot systems that can be readily manufactured,
- we can analyze single-photon as well as few photon Signal/Control quantum regimes,
- we can analyze transient phase-dependent response of a quantum dot system on a pico-second time scale,
- we can expand our results to include feed-back control for automatic phase detection,
- we can extend our analysis to consider effects of squeezed states for continuous variable polarization Stokes parameters,
- we can straightforwardly expand our results to include a Stokes parameter representation for an arbitrarily polarized Signal beam.

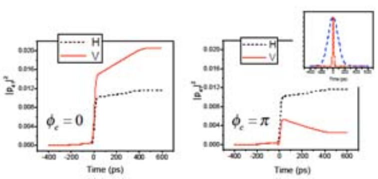
Benefits to NASA and JPL (or significance of results):

This proposed work is in response to JPL's SURP fiscal year 2008 *strategic topic area 5 (to achieve breakthrough increases in interplanetary communications; 100-1000 times current capabilities) by development of low-mass, low-power telecommunications payloads for deep-space missions and resource-constrained in-situ spacecrafts.*

Starting from a previously demonstrated atom-based phase-controlled low-light-level switch [1] that has been shown to operate at slow (~millisecond or KHz) signal rates, one of our key objectives was the conceptual development of a phase-controlled switch that is built on GaAs nano-technology, and which ideally combines the benefits of the phase-controlled atom-based device of Ref. [1] with ultrafast (picosecond or THz) data rates. In addition, it ideally allows to approach the ultimate low-light level regime in which the signal transmission is based on few-photon optical pulses. Clearly, both the ultrafast regime as well as the quantum optical regime separately pose significant theoretical challenges, and these challenges are exacerbated by the combination of both the ultrafast and quantum optical effects in a unified theoretical approach.

In order to analyze the phase sensitivity of a generic 4-level system in the most general way, so that both ultrafast dynamics as well as quantum-optical effects can be treated on the same footing, we decided to utilize a density-matrix formulation and solve the dynamical equations for the full density matrix without any approximations directly through numerical integration. We have implemented the equations in a Fortran code. In its present version (which contains some extensions not included in the core equations listed above), the code contains 64,499 characters and 3,127 lines. We assume the quantum dot to be in a high-quality micro-cavity with cavity mode functions that have maxima (antinodes) at the position of the quantum dot.





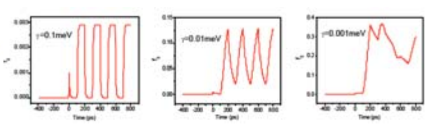


Figure 2- Control phase dependence of the Control absorption for horizontally (H) and vertially (V) polarized Signal

Figure 3. Time dependence of the Signal absorption for different de-phasing rates and a step-function phase variation .

Control

Figure 1. Level scheme and selection rules of the interface-disorder induced quantum dot. The material parameters used are from Ref. [2].

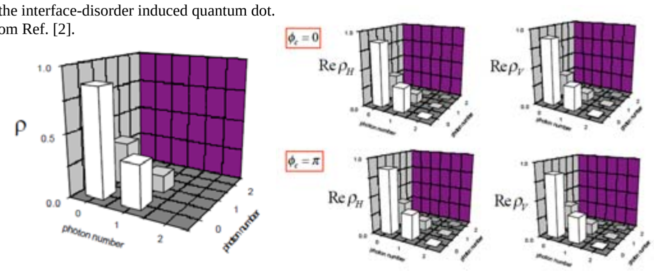


Figure 3. Reduced density matrix for the H/V polarized Signal photon field after the pulses are gone, for two different Control phases.

In this project, we have laid the theoretical foundation for the use of GaAs quantum dots in phase-sensitive BPSK receivers. Our work addresses several fundamental issues, such as the phase sensitivity in the quantum-optical (few photon) regime and selection rules in specific and available quantum dot systems. Due to the very general density-matrix approach, that allows us to study dynamic and quantum-optical effects within the same framework, we are in a position to compute any performance related quantity of the quantum dot system. Important initial results obtained in this project are the observation of phase sensitive response in the quantum-optical regime with one-photon truncated coherent states, and the surprising observation of the absence of frequency doubling response to phase-modulated control in the case of weak Pump beams and disorder-induced GaAs quantum dots. We would like to stress that solid theoretical foundation and large Fortran codes developed in this first year of the project, combined with the promising initial results, suggest that a continuation of the project may lead to tangible results that are related to NASA's communication applications and the quest of improved receiver technology through the use of quantum mechanical coherences.

References:

[1] H. Kang, G. Hernandez, J. Zhang, and Y. Zhu, "Phase-Controlled Light Switching at Low Light Levels," Physics Review A **73**, 011802 (2006)

[2] G. Chen, T.H. Stievater, E.T. Batteh, X. Li, D.G. Steel, D. Gammon, D.S. Katzer, D. Park, and L.J. Sham, "Biexciton quantum coherences in a single quantum dot", Phys. Rev. Lett. **88**, 117901 (2002)

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Publications:

[1] R. Binder, N.H. Kwong, and H. Javadi, "Phase-sensitive dynamical response of GaAs quantum dots", in preparation

[2] R. Binder, N.H. Kwong, and H. Javadi, "Phase-controlled interference and switching effects in semiconductor quantum dots in the few photon regime", in preparation

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